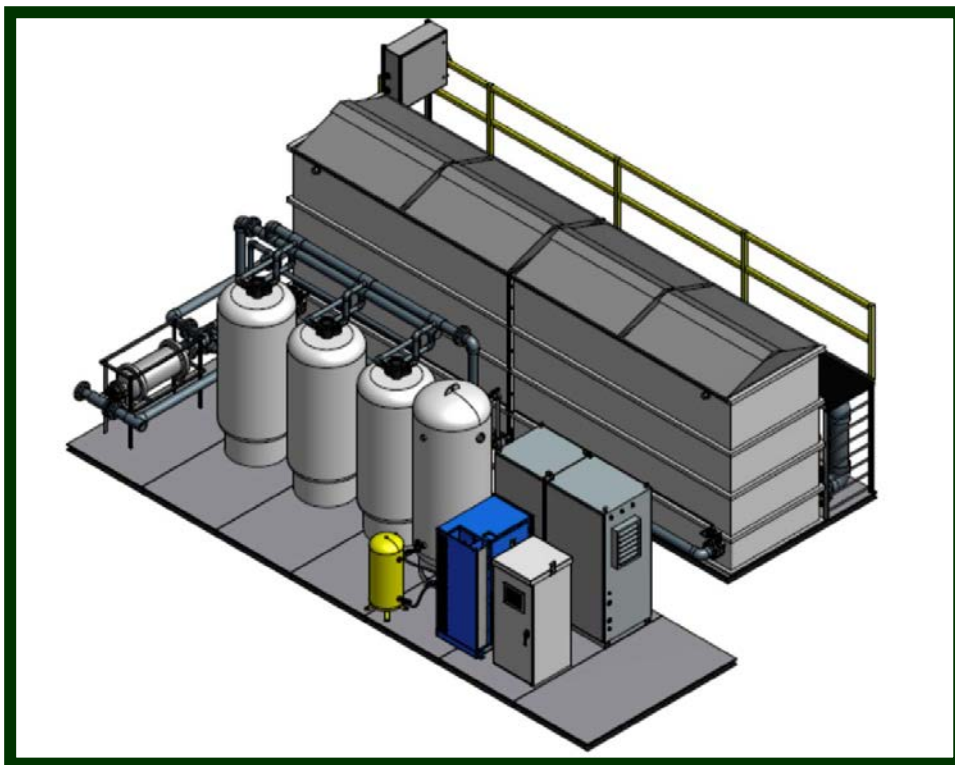


# ESTCP Cost and Performance Report

(ER-200541)



## Nitrate and Perchlorate Destruction and Potable Water Production Using Membrane Biofilm Reduction

January 2014

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# **COST & PERFORMANCE REPORT**

Project: ER-200541

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## ACRONYMS AND ABBREVIATIONS

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ASU	Arizona State University
CDPH	California Department of Public Health
CSTR	continuous stirred tank reactor
DBP	disinfection byproduct
DBP-FP	Disinfection byproduct formation potential
DO	dissolved oxygen
DOC	dissolved organic carbon
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
EVWD	East Valley Water District
FXB	fixed-bed bioreactor
GAC	granular activated carbon
g-H <sub>2</sub> /m <sup>2</sup> -day	grams of hydrogen per meter squared per day
gpm	gallons per minute
H <sub>2</sub>	hydrogen
HAA5	haloacetic acid five
HPC	heterotrophic plate count
IX	ion exchange
LEL	lower explosive limit
µg/L	micrograms per liter
MBfR	membrane biofilm reactor
MCL	maximum contaminant level
mg/L	milligrams per liter
mg-N/L	milligrams nitrogen per liter
mL	milliliters
MPN/mL	most probable number per milliliter
NDEA	N-nitrosodiethylamine
NDMA	N-nitrosodimethylamine
NDPA	N-nitroso-di-n-propylamine
ng/L	nanograms per liter
NO <sub>2</sub> <sup>-</sup>	nitrite
NO <sub>3</sub> <sup>-</sup>	nitrate
NTU	nephelometric turbidity units
ORP	oxidation-reduction potential

## ACRONYMS AND ABBREVIATIONS (continued)

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RASP	Rialto Ammunition Storage Point
RWQCB	Regional Water Quality Control Board
SDWA	Safe Drinking Water Act
TON	threshold odor number
THM-FP	trihalomethane formation potential
TTHM	total trihalomethane
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound
WCLC	West Coast Loading Corporation
WVWD	West Valley Water District



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## **EXECUTIVE SUMMARY**

### **OBJECTIVES OF THE DEMONSTRATION**

Perchlorate is a strong oxidizer that is primarily used in solid rocket fuels, fireworks, explosives, and road flares. While perchlorate can be generated from natural processes, the majority of occurrence in the United States (U.S.) is from anthropogenic sources. Perchlorate is a human health concern because it can prevent assimilation of iodide in the thyroid by competitively inhibiting its uptake. Iodide regulates normal functions of the thyroid and is critical in the growth and development of fetuses, infants, and children. Nitrate ( $\text{NO}_3^-$ ) is commonly found as a co-contaminant in water with perchlorate because ammonium nitrate is a main component in rocket fuel and explosives.

Anoxic biodegradation can be used to treat perchlorate and nitrate, and it can result in complete destruction of the contaminants. The membrane biofilm reactor (MBfR) process demonstrated in this project used the latest advances in membrane technologies and included anoxic biological reduction using a staged hydrogen-fed membrane biofilm reactor, aerobic biological stabilization, media filtration, and disinfection. The purpose of this Demonstration was to evaluate the feasibility of the MBfR to destroy perchlorate and nitrate in groundwater and produce potable water. Performance objectives were met for nitrate but not for perchlorate. Most of the perchlorate was destroyed, and the average effluent concentration was 9.2 micrograms per liter ( $\mu\text{g/L}$ ), compared to a performance objective of 6  $\mu\text{g/L}$ .

### **TECHNOLOGY DESCRIPTION**

The MBfR process uses permeable, but non-porous hollow-fiber membranes pressurized with hydrogen gas to promote autotrophic bioreduction of perchlorate to chloride ion and nitrate to nitrogen gas. Hydrogen is fed to the lumen of hollow-fiber gas-transfer membranes, and bacteria grow naturally as a biofilm on the exterior of the membranes exposed to contaminated water. The treatment system included two anoxic MBfRs operated in series to reduce oxygen to water, nitrate to nitrogen gas, and perchlorate to the chloride ion. Post-MBfR treatment processes included aeration to re-oxygenate the water, media filtration supplemented with a coagulant/filter aid to remove suspended solids, and disinfection using sodium hypochlorite.

### **DEMONSTRATION RESULTS**

Perchlorate was reduced from an average of  $154 \pm 5$   $\mu\text{g/L}$  to an average of  $9.2 \pm 2.3$   $\mu\text{g/L}$  in the effluent of the lag reactor during Steady State (94.4% reduction). While the treatment objective of 6  $\mu\text{g/L}$  was not met at all times, perchlorate removal was consistent (coefficient of variation was 0.75%). Special batch tests demonstrated that complete perchlorate removal was possible, but was commensurate with sulfate reduction and sulfide generation. Modeling and bench-scale studies conducted by Arizona State University (ASU) in parallel to the pilot studies demonstrated that complete perchlorate removal and minimal sulfide production could be achieved as long as the removal flux of nitrate and oxygen—expressed as stoichiometric hydrogen demand—was about 0.18 grams of hydrogen per meter squared per day ( $\text{g-H}_2/\text{m}^2\text{-day}$ ) in the second stage of the MBfR. Operation under these conditions in the laboratory prevented

overgrowth of sulfate reducing bacteria. Other differences between the laboratory and pilot-scale systems, such as trans-membrane liquid velocity and associated mass-transfer resistance, may have also led to different performance in the bench- and pilot-scale systems.

The MBfR was highly effective at removing nitrate. Total nitrogen (the sum of nitrate and nitrite) was reduced from an influent average of 9.0 milligrams nitrogen per liter (mg-N/L) to an average of  $0.12 \pm 0.07$  mg-N/L in the effluent of the lag reactor during Steady State (98.3% reduction). Nitrate reduction was consistently removed (coefficient of variation was 0.94%), with the highest effluent total nitrate only 0.24 mg-N/L.

Other drinking water treatment goals that were evaluated included disinfection, odor, turbidity, dissolved organic carbon (DOC), and pH. During Steady State, *Escherichia coli*, fecal coliforms, and total coliforms were below the detection limit (2/100 milliliters [mL]) in all post-disinfection samples. Heterotrophic plate counts (HPC) were on average 43 most probable number per milliliter (MPN/mL), and no samples were greater than the maximum contaminant level (MCL) of 500 MPN/mL. Disinfection byproducts were below regulatory limits. Haloacetic acids (HAA5) were below detection ( $< 6$   $\mu\text{g/L}$ ) and total trihalomethanes (TTHM) averaged 4.8  $\mu\text{g/L}$  compared to the MCL of 80  $\mu\text{g/L}$ . Nitrosamines were not detected. The average threshold odor number (TON) during Steady State was 2.2 compared to the U.S. Environmental Protection Agency (USEPA) National Primary Drinking Water Regulation's secondary standard for TON of three. An average turbidity of 0.27 nephelometric turbidity units (NTU) was observed at the filter effluent during Steady State. Media-filter optimization would have resulted in lower turbidities, but was not part of the study.

Comparing the MBfR system with ion exchange (IX) showed that the MBfR was more economical for nitrate removal, particularly when wastewater disposal for IX regeneration is included, since IX resin regeneration disposal costs are site-specific. Wastewater from the MBfR system, which includes media backwash water and MBfR sparging water, can be discharged through the municipal sanitary sewer. However, wastewater generated during IX regeneration cannot be directly discharged to a municipal sewer mainly because of the high salt concentrations. MBfR costs also were compared with results from the ESTCP project, "Direct Fixed-Bed Bioreactor (FXB) Biological Perchlorate Destruction Demonstration." The MBfR was shown to have similar or lower total treatment costs for nitrate removal.

## IMPLEMENTATION ISSUES

The MBfR system for treatment of nitrate and production of potable water was shown to be effective. The MBfR system is ready for applications involving treatment of drinking water sources contaminated with nitrate. Treatment of perchlorate to less than 6  $\mu\text{g/L}$  was not achieved consistently at the pilot scale. The parallel research conducted by ASU provides possible ways to address this current limitation. Conditional acceptance of the MBfR has been obtained from the California Department of Health Fish and Game Code. The first full-scale MBfR system for treatment of nitrate (ARoNite<sup>TM</sup>) in drinking water is in the process of being permitted at Cucamonga Valley Water District.

## **1.0 INTRODUCTION**

### **1.1 BACKGROUND**

Perchlorate is a strong oxidizer that is primarily used in solid rocket fuels, fireworks, explosives, and road flares. While perchlorate can be generated from natural processes, the majority of occurrence in the United States (U.S.) is from anthropogenic sources. Perchlorate is a human health concern because it can prevent assimilation of iodide in the thyroid by competitively inhibiting its uptake. Iodide regulates normal functions of the thyroid and is critical in the growth and development of fetuses, infants, and children (U.S. Environmental Protection Agency [USEPA], 2005).

Nitrate ( $\text{NO}_3^-$ ) is often found as a co-contaminant with perchlorate because ammonium nitrate is a main component in rocket fuel and explosives (Wang et al., 2002). Costs for mitigating perchlorate and nitrate contamination can be significant; thus, demonstration and validation of cost-effective treatment technologies is critical to the Department of Defense (DoD).

Anoxic biodegradation can be used to treat perchlorate and nitrate, and it can result in complete destruction of the contaminants. This is an advantage compared to ion exchange where the contaminants are not destroyed. Membrane biofilm reactor (MBfR) technology relies on autotrophic bacteria that use hydrogen as an electron acceptor and do not use organic carbon as a source for growth; instead, they grow using bicarbonate as a carbon source.

### **1.2 OBJECTIVES OF THE DEMONSTRATION**

The purpose of this demonstration was to evaluate the feasibility of the MBfR to destroy perchlorate and nitrate in groundwater and produce potable water at the pilot scale, evaluate process control parameters to optimize performance, and estimate full-scale technology costs. An additional objective was to obtain regulatory acceptance of the technology.

### **1.3 REGULATORY DRIVERS**

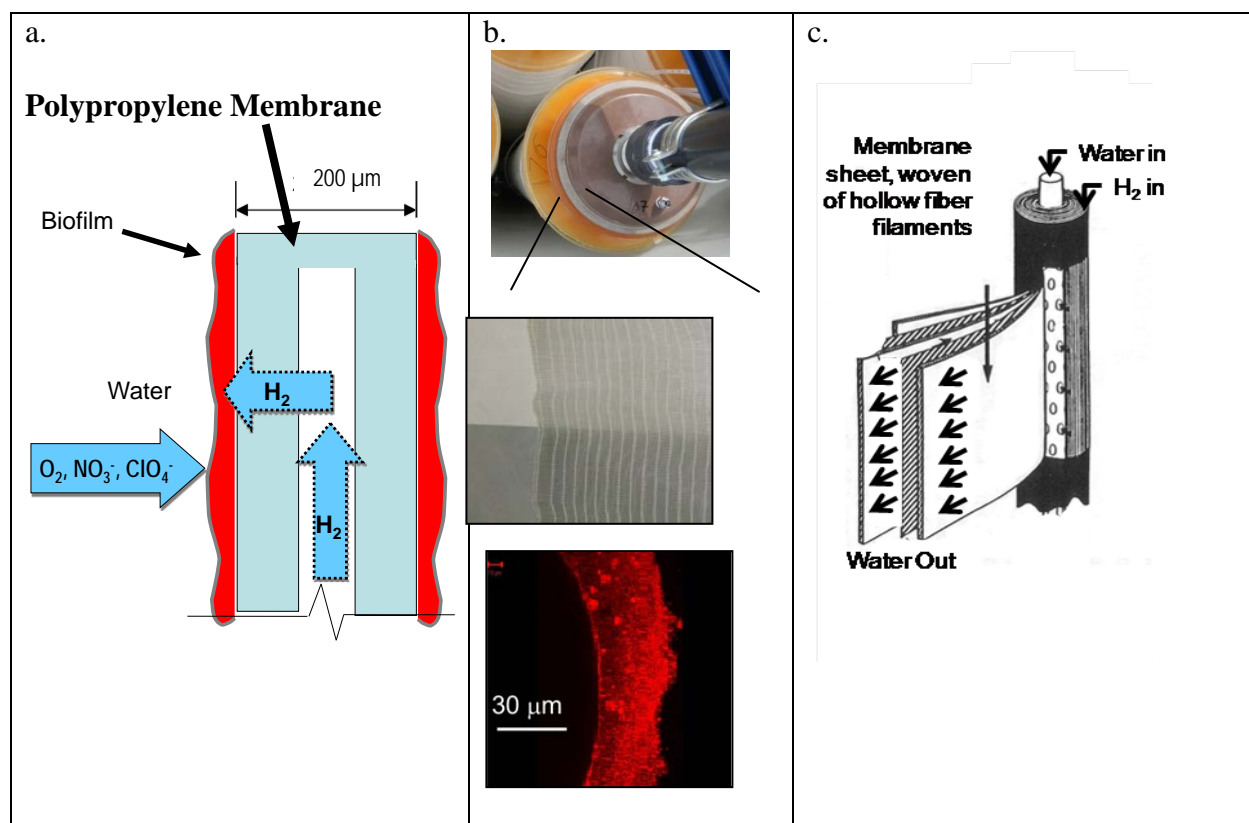
Massachusetts established a maximum contaminant level (MCL) for perchlorate of 2 micrograms per liter ( $\mu\text{g/L}$ ) in 2006, California established an MCL of 6  $\mu\text{g/L}$  in 2007, and New Jersey established an MCL of 5  $\mu\text{g/L}$  in 2009 (Lehman and Subramani, 2011). Perchlorate is also governed under the California's guidance document for the use of extremely impaired sources when the concentration exceeds 10 times the MCL (60  $\mu\text{g/L}$ ), the source water "is extremely threatened with contamination due to proximity to known contaminating activities," "contains a mixture of contaminants of health concern," or "is designed to intercept known contaminants of health concern" (California Department of Public Health [CDPH], 1997). In February 2011, the USEPA released the determination that perchlorate met the Safe Drinking Water Act (SDWA) criteria for regulation, and USEPA is currently in the process of establishing an MCL (Lehman and Subramani, 2011). Nitrate is regulated by the SDWA and has an established MCL of 10 milligrams of nitrate-nitrogen per liter ( $\text{mg-N/L}$ ). In addition, groundwater that is used as a drinking water source needs to comply with all applicable regulations under USEPA's SDWA. Several states have their own regulations that are more stringent than the SDWA.

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## 2.0 TECHNOLOGY DESCRIPTION

### 2.1 TECHNOLOGY OVERVIEW

The MBfR process is based on the latest advances in membrane technology and includes anoxic biological reduction using a staged hydrogen-fed membrane biofilm reactor followed by aerobic biological stabilization, media filtration, and disinfection. This technology builds upon a number of previously successful MBfR studies treating high concentrations of perchlorate and nitrate in groundwater (Adham et al., 2004; Chung et al., 2007; Lee and Rittmann, 2002; Nerenberg and Rittmann, 2004; Nerenberg et al., 2003; Nerenberg et al., 2002). The MBfR design uses permeable, but non-porous hollow-fiber membranes pressurized with hydrogen gas ( $H_2$ ). Hydrogen is fed to the lumen of hollow-fiber gas-transfer membranes, and bacteria grow naturally as a biofilm on the exterior of the membranes exposed to contaminated water (Figure 1a). Membrane sheets of woven hollow-fiber filaments are wrapped around an interior perforated core, and water flows out radially (Figure 1c). Hollow fiber membranes are widely used in a range of industries for bubble-less gas transfer. In the MBfR, bubble-less gas transfer allows delivery of hydrogen gas directly to the bacteria in the biofilm.



**Figure 1. Schematic of hydrogen-fed MBfR (a) membrane cross section, (b) woven fibers and biofilm, and (c) membrane module design.**

The treatment system for this demonstration included two anoxic MBfRs operated in series to reduce oxygen to water, nitrate to nitrogen gas, and perchlorate to the chloride ion. The first

MBfR vessel had seven membrane modules that were primarily used for reduction of oxygen and nitrate. The second MBfR vessel contained seven membrane modules and primarily reduced the remaining nitrate and perchlorate. Phosphorous was supplemented as a nutrient, and carbon dioxide was amended for pH neutralization, control of hardness precipitation, and as a carbon source for microbial cell synthesis. Post-MBfR treatment included proven processes that are necessary for drinking water treatment. These processes included aeration to re-oxygenate the water, media filtration supplemented with a coagulant/filter aid to remove suspended solids, and disinfection using sodium hypochlorite. For discharge of the water at the test site, additional post-treatment involved granular activated carbon (GAC) for volatile organic compounds (VOC) and ion exchange (IX) for perchlorate to meet California Regional Water Quality Control Board (RWQCB) permit requirements. The process flow diagram is provided in Figure 2.

## **2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY**

The membrane-based system for bioreduction of perchlorate and nitrate has the following advantages:

- Perchlorate and nitrate are biologically reduced to chloride, water, and nitrogen gas. Thus, the target contaminants are eliminated, not transferred to another phase, as is the case for IX resin, tailored activated carbon, and reverse osmosis.
- Hydrogen-based bio-reduction in the MBfR uses an inorganic electron donor (i.e., hydrogen) and an inorganic carbon source (i.e., bicarbonate or carbon dioxide) for autotrophic bacteria. This eliminates the need to supply an organic electron donor to support heterotrophic bacteria, as is the case for other biological treatment approaches such as fluidized bed reactors, packed or fixed bed reactors, and continuous stirred tank reactors. Using autotrophic bacteria can potentially lower the amount of biomass that is produced in the process and must ultimately be disposed.

Limitations of the technology include:

- The integration of the hydrogen-based MBfR with aeration and media filtration has not previously been tested for its ability to generate potable water. This demonstration project was specifically designed to provide data necessary to critically evaluate performance.
- The ability to maintain stable control of the biofilm and prevent fouling in the MBfR has not been demonstrated at the pilot scale. This demonstration project was specifically designed to address this limitation.
- The technology uses hydrogen, which is flammable. Engineering design of the MBfR system must comply with codes for design and operation of systems using hydrogen.
- Biological perchlorate treatment may require greater operator attention, as it may be less robust with respect to process upsets compared to IX systems. The overall economics of perchlorate treatment will drive any decision regarding the implementation of biological treatment.





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### 3.0 PERFORMANCE OBJECTIVES

Performance objectives were established for this demonstration to provide a basis for evaluating MBfR performance and cost for the reduction in perchlorate, nitrate, and nitrite concentrations in groundwater. The performance objectives apply to the complete MBfR and post treatment process train, as summarized in Table 1.

**Table 1. Performance objectives.**

Performance Objective	Data Requirements	Success Criteria	Performance Objective Met
<b>Quantitative Performance Objectives</b>			
Determine treatment effectiveness	Pre- and post-treatment concentrations of perchlorate, nitrate, and $\text{NO}_2^-$	Post-treatment concentrations: $\text{ClO}_4^- \leq 6.0 \mu\text{g/L}$ $\text{NO}_3^- \leq 0.5 \text{ mg-N/L}$ $\text{NO}_2^- \leq 0.5 \text{ mg-N/L}$	No – lag reactor effluent perchlorate was $9.2 \mu\text{g/L}$ (average) during Steady State and was removed by 94.4%.  Yes – nitrate and nitrite were below $0.5 \text{ mg-N/L}$ for all samples at the lag effluent during Steady State.
Determine disinfection effectiveness	Post disinfection concentrations of fecal coliforms, total coliforms, HPC	Post-disinfection concentrations: fecal coliforms below detection total coliforms below detection HPCs $\leq 500 \text{ MPN/ mL}$	Yes – fecal and total coliforms and <i>E. coli</i> were below the detection limit of 2 MPN/100 mL in all post-disinfection samples during Steady State. HPCs were on average 43 MPN/mL during Steady State and no sample was greater than 500 MPN/mL.
Determine ability to meet drinking water treatment primary and secondary MCLs	Post disinfection odor, turbidity, organic carbon, and pH	$\text{TON} \leq 3$  Turbidity $\leq 0.2 \text{ NTU}$  DOC increase $\leq 0.2 \text{ mg/L}$  $6.5 \leq \text{pH} \leq 8.5 \text{ SU}$	Yes - TON was 2.2 on average, but 3 of 12 samples were above a TON of 3. These 3 samples were associated with process shutdowns because of high winds.  No – The average turbidity was 0.27 NTU, and turbidity exceeded 0.2 NTU 33% of the time based on online measurements. Further optimization can address this issue.  No – DOC increased an average of 0.4 mg/L from the system influent to post-disinfection during Steady State. However, this metric for distribution system stability is not driven by regulation and may be acceptable.  Yes – pH was between 6.5 and 8.5 in all samples analyzed.
Reliability	Operating Records	$\geq 95\%$ uptime during Steady State operational period	Yes – system up time during Steady State was 98%.

**Table 1. Performance objectives (continued).**

<b>Performance Objective</b>	<b>Data Requirements</b>	<b>Success Criteria</b>	<b>Performance Objective Met</b>
<b>Qualitative Performance Objectives</b>			
Safety	Operating records	No reportable health and safety incidents	Yes – there were no reportable health and safety incidents.
Permit Compliance	Monthly permit reports	No violations	Yes – there were no permit violations.
Regulatory Acceptance	Review by CDPH	Obtain letter of conditional acceptance from the CDPH	Yes – Conditional acceptance for treatment of nitrate was received on July 26, 2013.

DOC = dissolved organic carbon

HPC = heterotrophic plate counts

mg/L = milligram per liter

MPN/mL = most probable number per milliliter

NTU = nephelometric turbidity unit

TON = threshold odor number

## 4.0 SITE DESCRIPTION

The first stage of this project involved a pilot-scale demonstration of the MBfR at East Valley Water District (EVWD) in San Bernardino, California, using water from EVWD Well 28A. Results from this pilot-scale demonstration are discussed in the ESTCP Final Report (Evans et al., 2013). The second stage of this project was conducted at West Valley Water District's (WVWD) Well 22 in Rialto, California (Figure 3). WVWD Well 22 was a former agricultural well that was not being used as a water source prior to the demonstration. Contamination of perchlorate and VOCs is believed to have originated from weapons/explosives manufacturing and storage at the Rialto Ammunition Storage Point (RASP) northwest of the well site. The RASP was operated by the U.S. Army from 1942 to 1945. The site was owned and occupied by West Coast Loading Corporation (WCLC) until 1957. WCLC performed the loading, assembly and testing of munitions with perchlorate for the U.S. Army and Navy. B.F. Goodrich owned and operated the site for propellant manufacturing and testing until 1963. The site was sold by B.F. Goodrich in the 1960s and was subsequently used by various defense contractors, fireworks, and pyrotechnics companies. The nearby Mid-Valley Sanitary Landfill is another known source of VOCs (GeoSyntec, 2005).

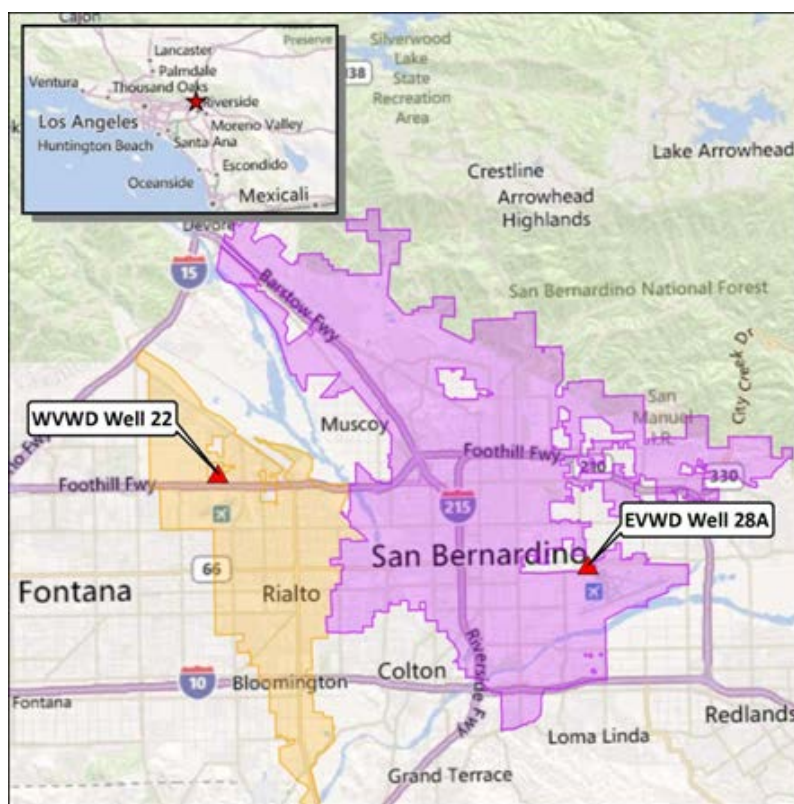


Figure 3. Site vicinity map.

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## 5.0 TEST DESIGN

This section provides a detailed description of the MBfR system design, operation, and testing conducted for the demonstration.

### 5.1 CONCEPTUAL EXPERIMENTAL DESIGN

This 9-month demonstration was initiated in April 2011 using perchlorate- and nitrate-contaminated groundwater from WVWD Well 22 in Rialto, California. The experimental design had four phases (Figure 4). Start-Up was initiated after construction of the system was complete and the system was placed on-line. During Start-Up, indigenous bacteria colonized the membranes to form an active biofilm. The second phase was Optimization during which operational conditions were varied to assess system performance. The third phase was a period of Steady State to assess process stability and sensitivity to changes in influent water quality conditions. The final stage of the demonstration was the Challenge phase. This included intentional process upsets to assess resiliency and reliability of the technology.

Start-Up	<ul style="list-style-type: none"><li>• Constructed system and initiated operations</li><li>• Colonized reactors with indigenous bacteria</li><li>• MBfR effluent goal of 6 µg/L perchlorate and 0.5 mg-N/L nitrate</li><li>• Tracer Testing</li></ul>
Optimization	<ul style="list-style-type: none"><li>• Varied feed flow rates</li><li>• Varied recycle ratios</li><li>• Batch Testing</li></ul>
Steady State	<ul style="list-style-type: none"><li>• Operated at optimal conditions for 1 month</li><li>• Full characterization of system performance</li></ul>
Challenge	<ul style="list-style-type: none"><li>• Perturb MBfR system through series of upsets</li><li>• Loss of electron donor - shut off hydrogen</li><li>• Power failure - shut off system</li></ul>

**Figure 4. Experimental design.**

### 5.2 BASELINE CHARACTERIZATION

Table 2 provides a summary of Well 22 water quality, which was the influent to the MBfR treatment system.

**Table 2. Summary statistics for influent water quality at Well 22 throughout the demonstration from April 2011 to January 2012.**

Analyte	Units	Average	Standard Deviation	Count
Alkalinity	mg/L as CaCO <sub>3</sub>	150	11.3	28
Hardness	mg/L as CaCO <sub>3</sub>	200	7.5	27
Nitrate	mg-N/L	8.82	0.38	32
Perchlorate	µg/L	170	17	70
pH	SU	7.5	0.11	71
Sulfate	mg/L	21	0.85	27
Trichloroethene	mg/L	54	7.0	28
Total dissolved solids	mg/L	260	15	28

### 5.3 TREATABILITY OR LABORATORY STUDY RESULTS

Numerous bench- and pilot-scale studies have been conducted demonstrating the feasibility of hydrogen MBfR for treatment of perchlorate and nitrate and are summarized in the ESTCP Final Report (Evans et al., 2013). Additional laboratory work was conducted in conjunction with the field effort by Arizona State University (ASU) and is reported separately (Rittmann et al., 2013). The ASU Team carried out multiple experiments to decipher why the two-stage MBfR system did not achieve the 6-µg/L effluent perchlorate goal. The team carried out extensive analyses of hydrogen, oxygen, nitrate, perchlorate, and sulfate fluxes during the pilot study. ASU also carried out bench-scale MBfR experiments and developed mechanistic mathematical models to identify and quantify the kinetic and ecological mechanisms underpinning the performance of the pilot and bench-scale MBfRs.

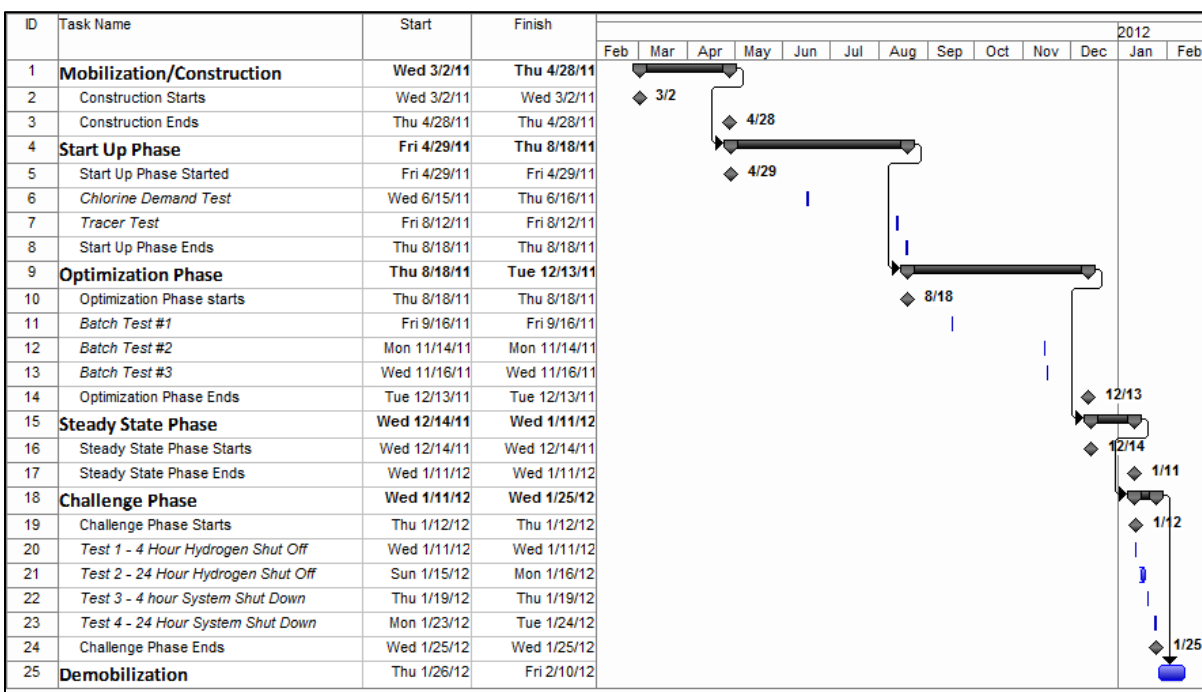
The modeling and bench-scale tests conducted by ASU showed no intrinsic roadblock for achieving a very low perchlorate concentration in the absence of sulfide generation. Attainment of this goal would require managing nitrate and oxygen loading to promote perchlorate-reducing bacteria growth and suppress sulfate reduction. If a two-stage system is used, particular attention has to be paid to nitrate and oxygen loading to the lag MBfR. The ASU results suggest that the lag MBfR should have a total hydrogen demand flux for nitrate and oxygen of around 0.18 grams hydrogen per meter squared per day ( $\text{g-H}_2/\text{m}^2\text{-day}$ ) to achieve desired perchlorate reduction without significant sulfate reduction.

### 5.4 FIELD TESTING

The field demonstration was comprised of four phases of testing including Start-Up, Optimization, Steady State, and Challenge. In addition to what was described in Section 5.1, operational parameters including flow rate, recycle flow rate, hydrogen pressure, gas sparge frequency, and the gas used for sparging were varied during optimization. Batch tests were conducted to evaluate mass transfer limitations, determine whether reduction of perchlorate concentrations to lower detection limits was possible, and determine how sulfide production correlated with perchlorate reduction. The Steady State phase was conducted from days 230 to 258 and the system was operated under optimal conditions. Finished water quality and aesthetics were assessed including turbidity, disinfection by-products (DBP), DBP formation potential (DBP-FP), nitrosamines, DOC, and TON. The Challenge phase included a series of intentional system upsets followed by system monitoring to assess system resiliency and stability. Hydrogen



shutoff was conducted to simulate loss of electron donor. Complete system shutdown tests were conducted to simulate power failure and shutdown of all operations. The dates and durations of each phase and test conducted are shown in Figure 5.



**Figure 5. Demonstration schedule.**

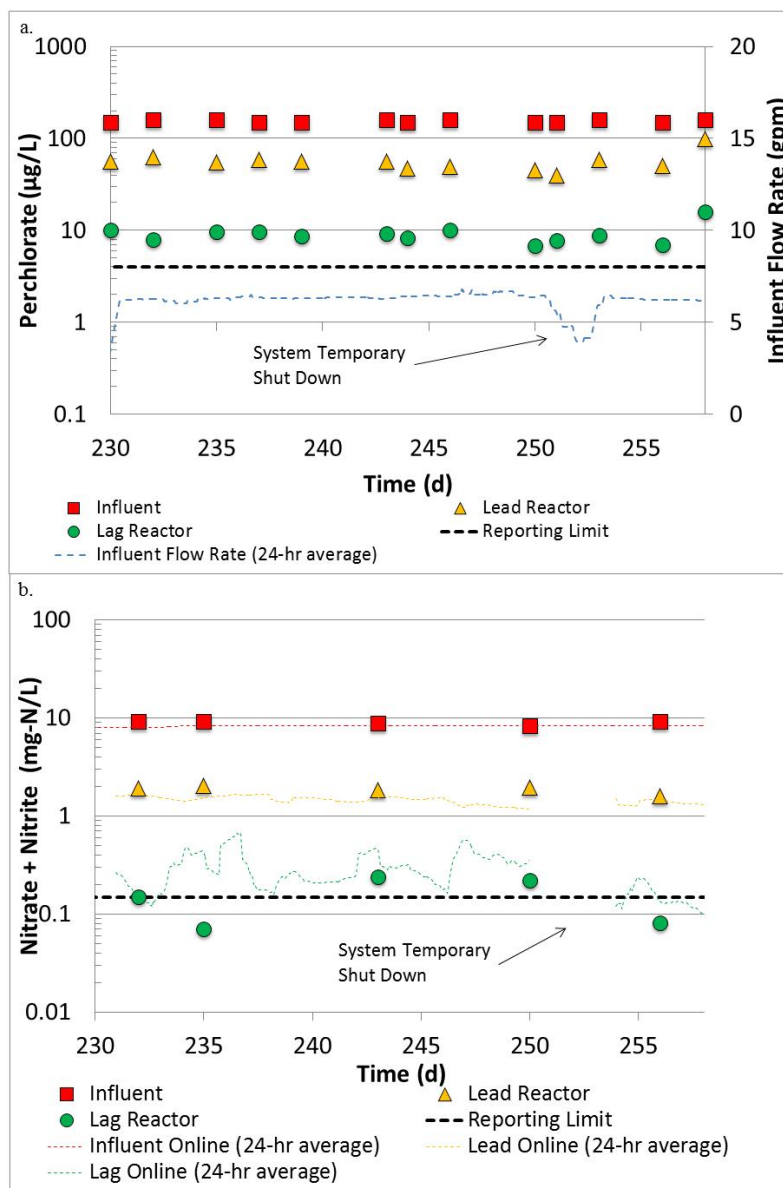
## 5.5 SAMPLING METHODS

The primary sampling locations included the influent groundwater (MBfR influent), MBfR lead and lag effluents, and the post-aeration, treatment process (i.e., media filter, bag filter, GAC, and IX) effluents. Most of the samples were grab samples, except for the MBfR sparge and filter backwash samples, where composites were collected. Sulfide, nitrate, nitrite, dissolved oxygen (DO), and chlorine residual were measured in the field using test kits. Temperature, oxidation-reduction potential (ORP), turbidity, and pH were measured using hand-held probes. On-line monitoring data were also collected continuously through the operator interface terminal for nitrate, pH, ORP, and temperature. The sampling frequency varied between once a week to three times a week depending on the parameter and phase of the demonstration. Samples were also sent to a certified laboratory for analysis of various parameters. See the ESTCP Final Report for details regarding analytical methods (Evans et al., 2013).

## 5.6 SAMPLING RESULTS

This section summarizes the results of the demonstration with a focus on Steady State operation. Complete demonstration results are presented in the ESTCP Final Report (Evans et al., 2013). Perchlorate and nitrate removal during Steady State was consistent over time (Figure 6). Perchlorate was reduced from an average of  $154 \pm 5$   $\mu\text{g/L}$  to an average of  $9.2 \pm 2.3$   $\mu\text{g/L}$  in the effluent of the lag reactor during Steady State (94.4% reduction). While perchlorate was on

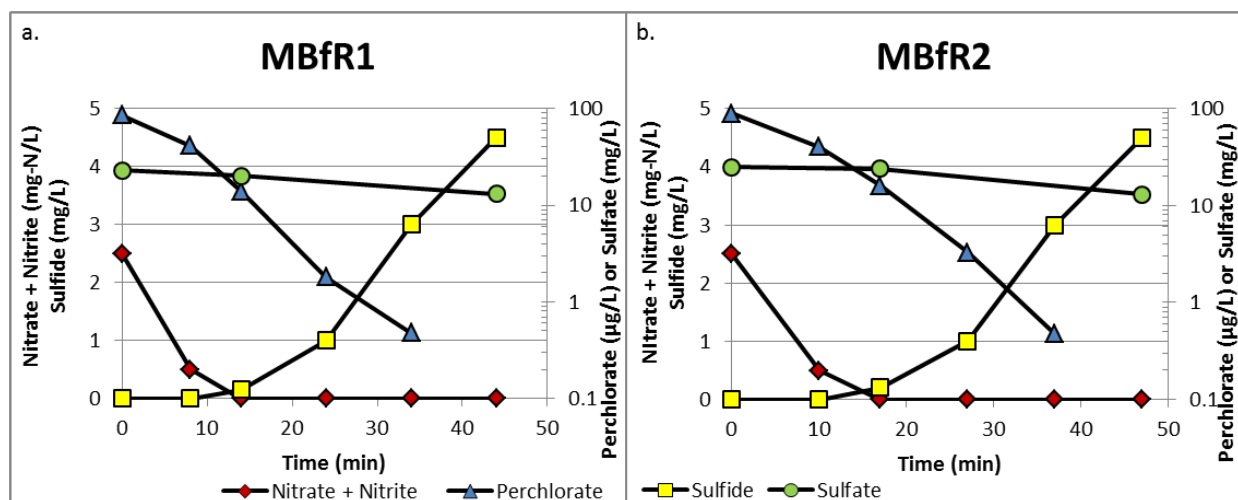
average above the treatment objective of 6  $\mu\text{g/L}$ , nitrate met the treatment objective of 0.5  $\text{mg/L}$  in the effluent at all times. Nitrate+nitrite were reduced from an influent average concentration of 9.0  $\text{mg-N/L}$  to an average of  $0.12 \pm 0.07 \text{ mg-N/L}$  at the MBfR lag effluent (98.3 % reduction).



**Figure 6. Steady State MBfR perchlorate and flow rate (a) and total nitrate+nitrite (b).**

Batch tests were conducted to determine whether perchlorate concentrations could meet the performance objective of 6  $\mu\text{g/L}$  or whether some inhibitory conditions (microbial or other) were present and hindering performance (Figure 7). Perchlorate was removed to less than 0.5  $\mu\text{g/L}$  and total nitrogen (the sum of nitrate and nitrite) was removed to below detection in MBfR1 and MBfR2 in the batch experiments. However, removal of perchlorate to concentrations below the performance objective coincided with the onset of sulfate reduction. These results agree with previous research which demonstrated a clear hydrogen utilization preference: oxygen, followed

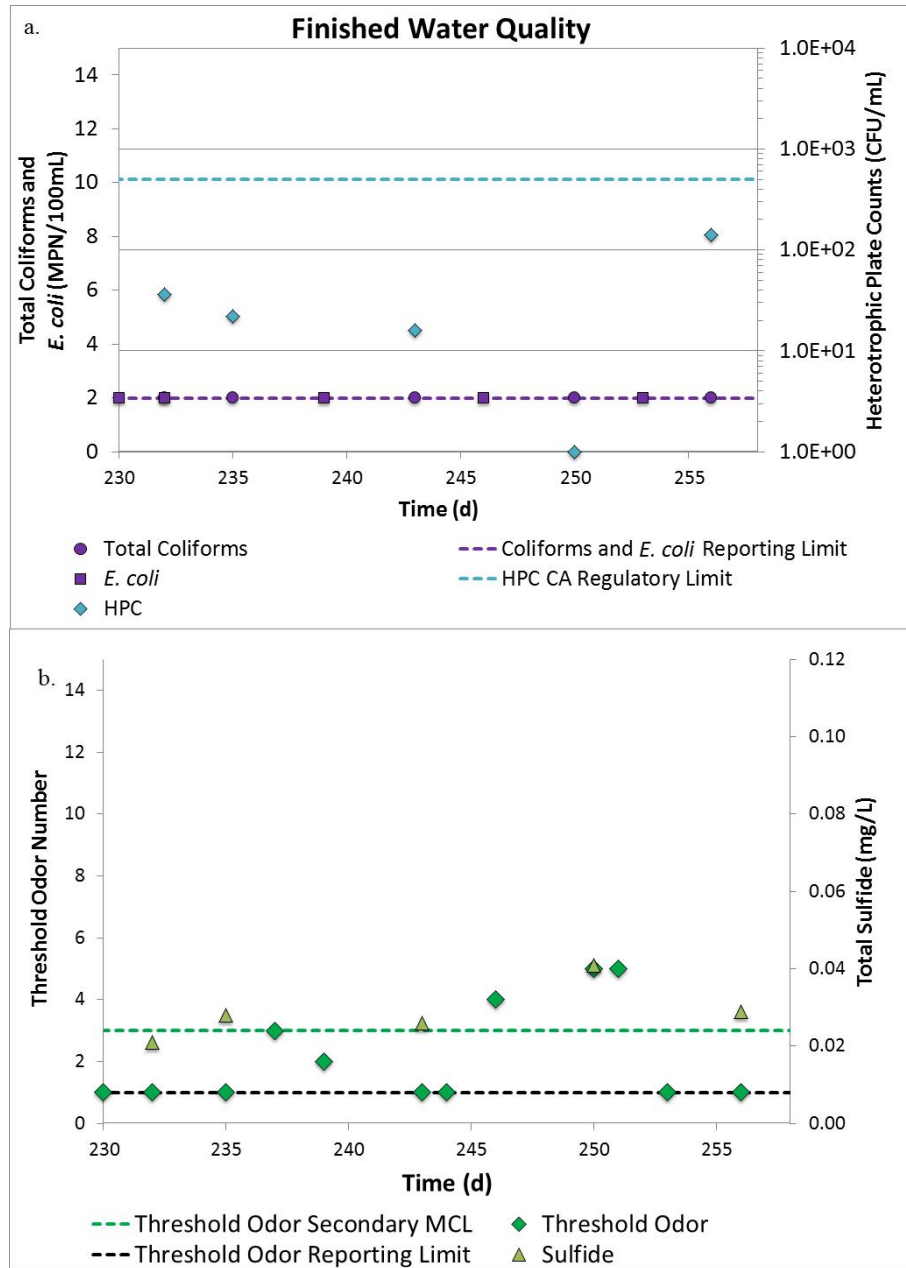
by nitrate, nitrite, and then perchlorate (Ziv-El and Rittmann, 2009). Nevertheless, the results demonstrate that complete removal of perchlorate in the two-stage MBfR perchlorate was possible.



**Figure 7. Preliminary batch test for MBfR1 (a) and MBfR2 (b).**

Optimization involved testing a range of conditions including altering influent flow rates and thus electron acceptor loading, MBfR vessel recycle flow rates to alter mass transfer rates, hydrogen pressure to alter electron donor delivery capacity, sparge frequencies, and sparge gases (i.e., use of nitrogen gas compared to compressed air). Operation under a range of influent flow rates, recycle flow rates, and hydrogen pressures resulted in destruction of most, but not all perchlorate – optimization was not able to reduce perchlorate consistently to less than 6 μg/L in the lag effluent. Liquid-phase mass transfer resistance was controlling the rate of perchlorate reduction and may have played a role in limiting complete perchlorate reduction. Studies conducted by ASU suggested that balancing of oxygen, nitrate, and perchlorate fluxes also played an important role in achieving complete perchlorate reduction, while not promoting overgrowth of sulfidogenic bacteria and resultant sulfate reduction (Rittmann et al., 2013).

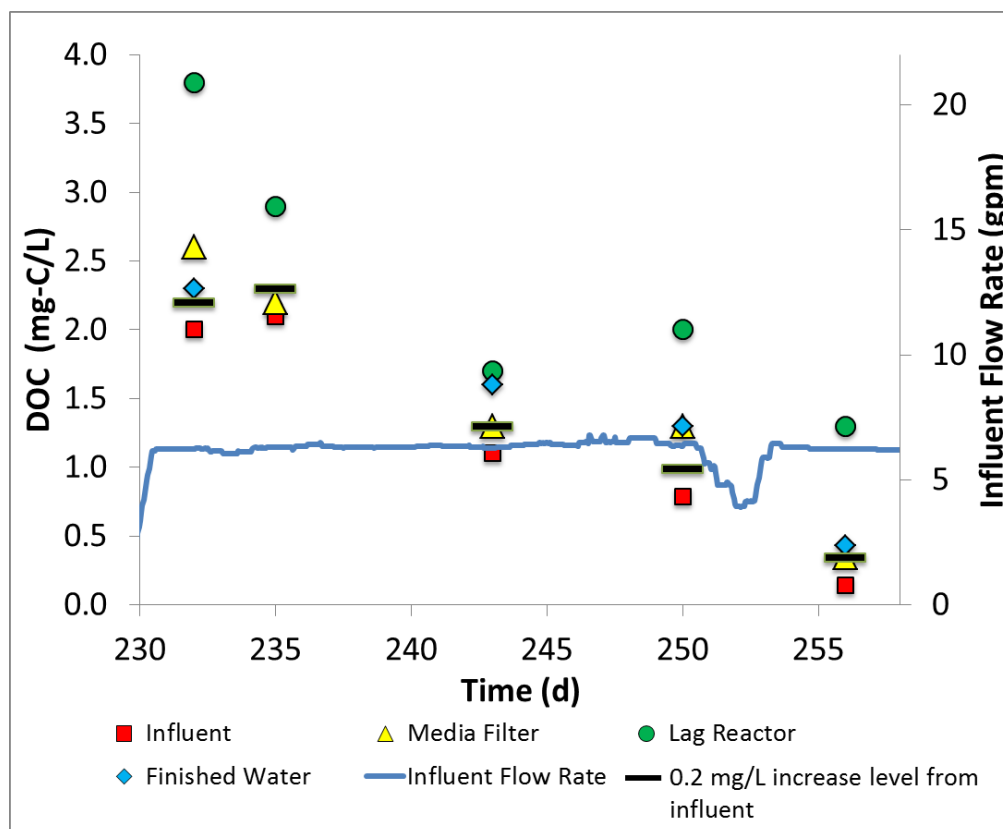
All samples collected from the finished water were below drinking water standards for *Escherichia coli* (*E. coli*), total coliforms, fecal coliforms, and HPCs (Figure 8a). TON was below the secondary MCL of 3, in all but three samples (Figure 8b). Those were on days 246, 250, and 251, during which system shutdowns associated with high winds occurred, the system operated in batch mode, and sulfide generation occurred.



**Figure 8. Steady State finished water quality bioindicators (a), sulfide, and odor (b).**

The performance objective for DOC was to have less than a 0.2-mg/L increase from the system influent to the finished water (Figure 9). DOC increased  $1.1 \pm 0.5$  mg/L from the influent to the MBfR lag, but subsequently decreased  $0.8 \pm 0.3$  mg/L in the media filter, leading to a net increase of  $0.4 \pm 0.1$  mg/L from the influent to the finished water during Steady State. Filtration removed most DOC produced in the MBfR. Influent DOC concentrations were uncharacteristically high (above 1 mg/L) in three of the five time points tested. The average influent DOC was  $0.56 \pm 0.38$  mg/L prior to Steady State. It is not known why concentrations in the raw feed water were so high at the beginning. This higher than normal organic loading may have resulted in increased biomass production, thus increasing the effluent DOC. While the goal for this project was less

than a 0.2 mg/L increase, the metric is not driven by regulation, and requirements for biological stability are specific to each drinking water distribution system. The increase of 0.4 mg/L DOC may not be all biodegradable DOC and may be stable in some distribution systems.



**Figure 9. Steady State treatment system DOC.**

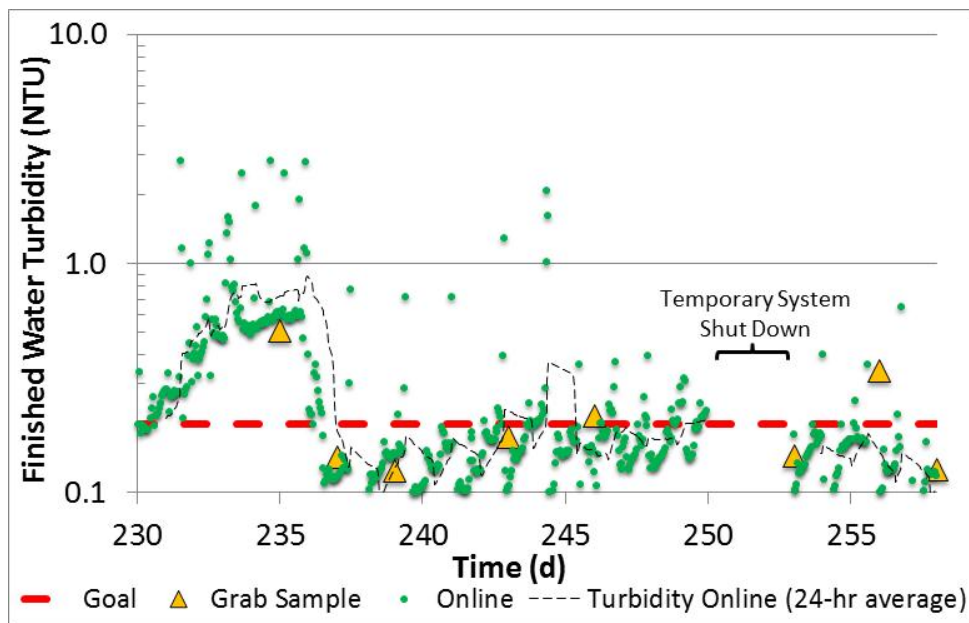
DBPs including haloacetic acid 5 (HAA5) and total trihalomethanes (TTHM) were measured in the finished water (Table 3). DBPs were below the MCL in all samples. DBP-FP was tested to determine DBPs generated during worst-case conditions; concentrations were significantly lower than the MCL (< 20% of the MCL). Nitrosamines including N-nitrosodiethylamine (NDEA), N-nitrosodimethylamine (NDMA), and N-nitroso-di-n-propylamine (NDPA) were below their respective CDPH Notification Level of 10 nanograms per liter (ng/L), or 0.01 µg/L, in the finished water. Nitrosamines are emerging contaminants that are not currently regulated for drinking water (e.g., no MCL) but are being evaluated by the USEPA.

**Table 3. Steady State finished water disinfection byproducts.**

Analyte	Average	Max	MCL
HAA5 (µg/L)	<6	<6	60
HAA6 (µg/L)	<7	<7	--
TTHMs (µg/L)	4.8	12	80
Maximum THM-FP (µg/L)	14.6	47	--
Nitrosamines (µg/L)	<0.0019	<0.0019	--

THM-FP = Trihalomethane Formation Potential

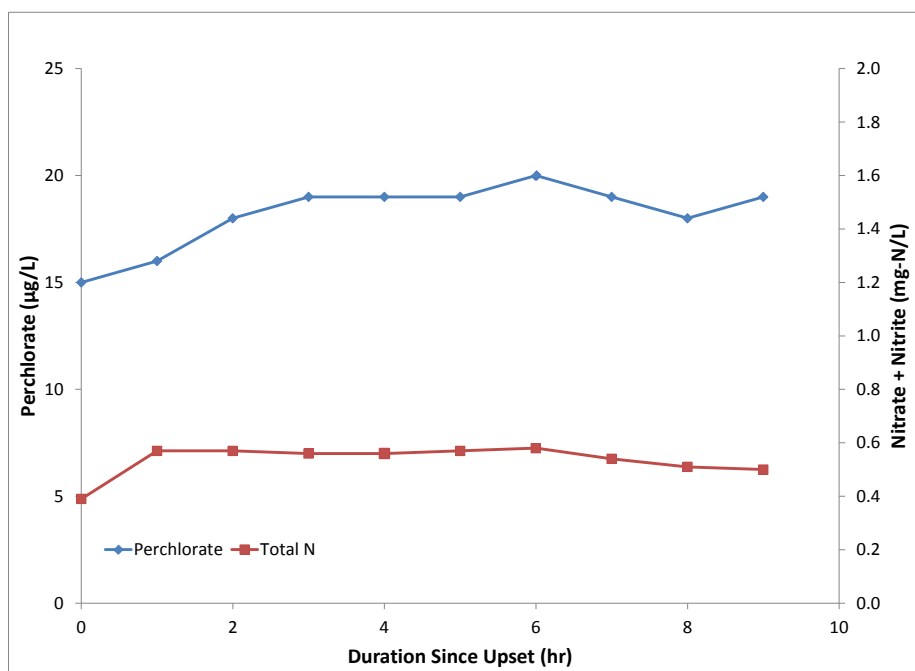
Finished water turbidity was near the treatment objective of 0.2 NTUs, with an average of 0.27 NTU (Figure 10). Turbidity was below 0.2 NTU 67% of the time based on on-line turbidity measurements. The Surface Water Treatment Rule requires that turbidity always be below 1 NTU and that 95% of the samples be less than 0.3 NTU. Readings where turbidity was above 0.2 NTU were primarily from days 230 to 235. During this time, a noticeable sulfur odor was present in the aeration tank. Sulfate was being reduced to sulfide and possibly elemental sulfur due to strongly reducing conditions in the MBfR. Colloidal sulfur may have contributed to higher turbidity readings. Optimization of media filtration was not conducted and would likely have improved turbidity removal.



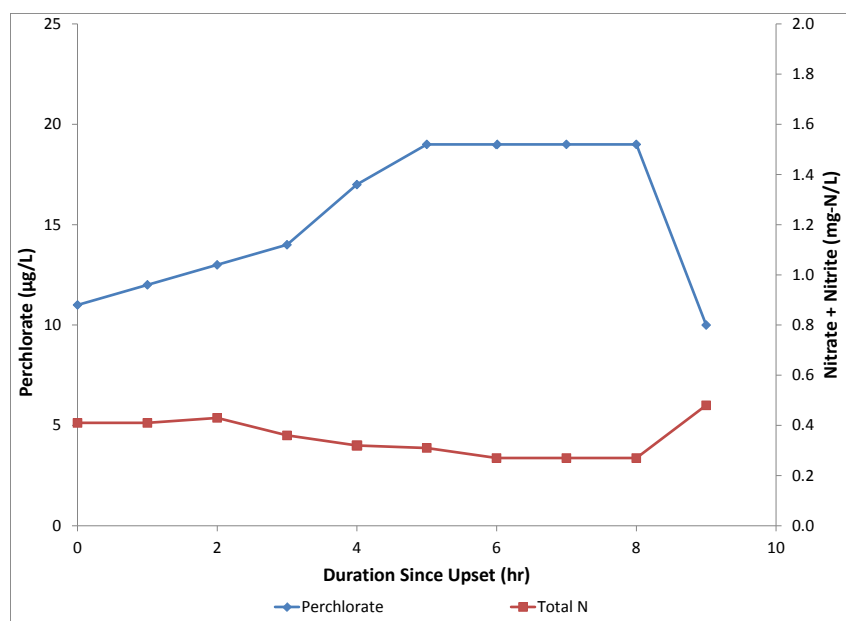
**Figure 10. Steady State finished water turbidity.**

The Challenge phase evaluated four intentional upset conditions: turning off the hydrogen supply for 4 and 24 hours, and turning the system off completely for 4 and 24 hours. For the hydrogen-supply tests, the concentrations of perchlorate and nitrate increased when hydrogen was off, and then steadily dropped over a period of about 8 to 10 hours when hydrogen was turned back. This corresponded well with the hydraulic residence time between the lag reactor and the finished water monitoring point. In both situations, nitrate recovered to less than 1 mg-N/L within the 10-hour period of monitoring. While perchlorate did not reach pre-upset concentrations within the monitoring period, the concentration would likely recover within 12 hours based on these first-order rate constants. The recovery trends were indicative of high reactor dispersion and continuous stirred tank reactor (CSTR) behavior.

Turning off the power supply did not have strong impacts on effluent water quality after the 4-hour shut-off (Figure 11) or the 24-hour shut-off period (Figure 12), as concentrations remained relatively constant. For these cases, the reactors went into a batch reactor mode, which resulted in more contact time with the contaminated water. While sulfide was not monitored in any of the Challenge phase tests, this would be helpful to be included in a monitoring program for a full-scale system for potential odor issues.



**Figure 11. Perchlorate and total nitrogen concentrations at the finished water after a 4-hour shut-off of power.**



**Figure 12. Perchlorate and total nitrogen concentrations at the finished water after a 24-hour shut-off of power.**

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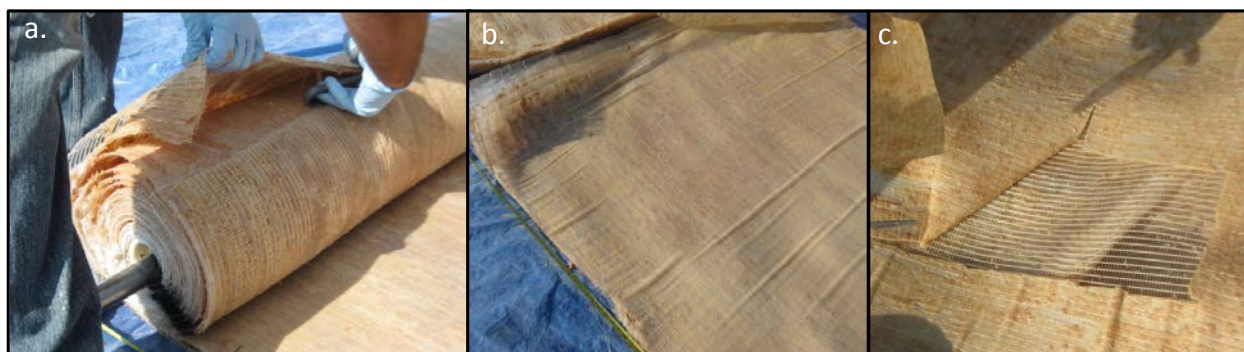


## 6.0 PERFORMANCE ASSESSMENT

This section includes an assessment of technology performance that is supported by data presented in Section 5.

### 6.1 TREATMENT EFFECTIVENESS

The MBfR was a reliable method for treating nitrate, and while perchlorate was not treated to below 6  $\mu\text{g/L}$ , it was consistently reduced by more than 90%. Biomass was visually observable on the membrane surfaces during an autopsy of a reactor (Figure 13). Visually, the biomass was uniformly light brown in color rather than black, indicating the biomass was not highly reduced. Reliability of the system is discussed in Section 6.4.



**Figure 13. Autopsy of MBfR reactor modules.**

#### 6.1.1 Perchlorate

Perchlorate was reduced from an average of  $154 \pm 5 \mu\text{g/L}$  to an average of  $9.2 \pm 2.3 \mu\text{g/L}$  in the effluent of the lag reactor during Steady State (94.4% reduction). While the treatment objective of 6  $\mu\text{g/L}$  was not met, perchlorate was consistently removed with little variation (coefficient of variation was 0.73%).

Batch tests demonstrated that complete perchlorate removal was possible, but sulfate reduction and sulfide generation began. Modeling and bench-scale studies by ASU demonstrated that complete perchlorate removal was observed with minimal sulfide production if the removal flux of nitrate and oxygen – expressed as stoichiometric hydrogen demand – was about  $0.18 \text{ g-H}_2/\text{m}^2\text{-day}$  (Rittmann et al., 2013). Other differences between the laboratory and pilot-scale systems, such as trans-membrane liquid velocity and associated mass-transfer resistance, may have also led to different performance in the bench- and pilot-scale systems.

#### 6.1.2 Nitrate and Nitrite

This demonstration validated the technical feasibility of the MBfR for treatment of nitrate. Total nitrogen (the sum of nitrate and nitrite) was reduced from an influent average of 9.0 mg-N/L to an average of  $0.12 \pm 0.07 \text{ mg-N/L}$  in the effluent of the lag reactor during Steady State (98.3% reduction). Thus, the treatment objective of 0.5 mg-N/L was met. Nitrate reduction was

consistently removed with little variation (coefficient of variation was 0.94%) with the highest total nitrate concentration of 0.24 mg-N/L. A key finding during Steady State was that 79% of nitrate was reduced across the lead reactor with an average lead effluent concentration of  $1.8 \pm 0.16$  mg-N/L. As such, a full-scale system could include single-stage operations depending on nitrate treatment goals, thus decreasing capital and operational costs and system footprint.

## **6.2 DISINFECTION EFFECTIVENESS**

Disinfection was accomplished using sodium hypochlorite with a free chlorine residual of 0.2 mg/L to meet disinfection requirements. Fecal coliforms, total coliforms, *E. coli*, and HPCs were used as indicator parameters for disinfection performance. Fecal and total coliforms and *E. coli* were below the detection limit (2/100 milliliter [mL]) in all samples during Steady State. HPCs were on average 43 MPN/mL, and no sample was greater than 500 MPN/mL during Steady State. Thus, the performance objective for disinfection effectiveness was met.

## **6.3 ABILITY TO MEET DRINKING WATER TREATMENT PRIMARY AND SECONDARY MCLS**

This section addresses the ability of the MBfR to address primary and secondary MCLs and other constituents relevant to production of drinking water. Trichloroethene was present in the MBfR influent, but was not removed. Trichloroethene removal was not an objective of this demonstration.

### **6.3.1 Odor**

The performance objective for the TON was less than or equal to three. An average TON of 2.2 was observed during Steady State; however, three of the 12 samples collected were above the performance objective. The three samples were associated with weather-related process shutdowns and accumulation of sulfide at a concentration of 0.04 mg/L. This concentration of sulfide can be mitigated by a more rigorous aeration step.

### **6.3.2 Turbidity**

Media filtration in combination with a coagulant filter aid was employed downstream of the MBfR to meet the performance objective of less than or equal to 0.2 NTU in the finished water. An average turbidity of 0.27 NTU was observed from online measurements during Steady State. However, there were several instances where turbidity was greater than 1 NTU. Turbidity was below 0.2 NTU approximately 67% of the time, and thus this performance objective was not met. Most of the data when turbidity was above 0.2 NTU were from days 230 to 235. During this time, a noticeable sulfur odor was present in the aeration tank. Colloidal sulfur likely generated by oxidation of biogenic sulfide may have contributed to higher turbidity readings. Prevention of sulfide production would minimize turbidity exceedances. An improvement to the design to increase the filter aid efficacy would be to move the filter aid injection location further upstream to increase mixing time. Additionally, a relatively new zeolite monomedia filter media (i.e., Next-Sand<sup>TM</sup>) was used in this study, thus turbidity results may not be translatable to conventional dual media (e.g., anthracite/sand) filtration.

### **6.3.3 DOC**

Residual biodegradable organic compounds in treated water can decrease water biostability and thus promote regrowth of organisms in distribution systems. DOC was selected as a surrogate indicator for biological stability, with a performance objective of no more than a 0.2-mg/L increase in DOC from the influent to the finished water. While this was a goal for the project, it was not driven by regulation, and requirements for stability are specific to each drinking water distribution system. The increase in DOC from the system influent to the finished water was on average 0.4 mg/L during Steady State. The net increase in system DOC exceeded the performance objective indicating that the performance objective was not met. Even though this goal was not met at all times, the increase may be acceptable and considered stable in some distribution systems. Water stability in the distribution system is affected by many factors and DOC is just one of those factors (Schneider et al., 2013).

### **6.3.4 pH**

The target for pH was between 6.5 and 8.5 SU, which is a secondary MCL. During the MBfR demonstration, the pH of the finished water remained within the performance standards ( $6.5 \leq \text{pH} \leq 8.5$ ). An average value of  $7.8 \pm 0.2$  SU was observed at the finished water during Steady State. The metric for this performance objective was met.

## **6.4 RELIABILITY**

This performance objective was to demonstrate greater than 95% uptime during Steady State. The system uptime during Steady State was 98% and this performance objective was met. System reliability was further evaluated during Challenge testing when either hydrogen (electron donor) or system power was shut off for either 4 hours or 24 hours. Hydrogen shut-off resulted in increased nitrate and perchlorate concentrations. System recovery to pre-upset conditions occurred within 10 hours for nitrate, and was anticipated to occur within 12 hours for perchlorate. The time for system recovery from hydrogen shut-off could be mitigated by operating the system in a batch recirculation mode. The system was relatively unaffected by power shut off as the bioreactor simply had more time to continue to degrade contaminants. Nitrate and perchlorate concentrations remained relatively constant following the 4-hour power shut-off period. Perchlorate increased transiently from about 10 to 20  $\mu\text{g/L}$  following the 24-hour power shut-off period.

## **6.5 SAFETY**

Safety concerns with this technology include use of a pressurized flammable gas, hydrogen, and other pressurized gases including nitrate and carbon dioxide. Generation of sulfide from sulfate can also cause inhalation hazards. There were no health and safety incidents reported during the demonstration. Hydrogen leaks were detected by a sensor and the system was automatically shut down for maintenance. Hydrogen sulfide and lower explosion limit (LEL) were monitored on a daily basis during the Optimization phase when a sulfide odor was noted by field staff. There were a few instances when the system was shut down due to a detection by the LEL sensor. However, no detections above the permissible exposure limit or threshold limit values were observed. The metric for this performance objective was met.

## **6.6 PERMIT COMPLIANCE**

The California RWQCB reviewed the Demonstration Plan and approved discharge of 43,200 gallons per day of treated groundwater back into the ground via a French drain. The system influent was monitored for VOCs and the effluent was monitored for flow rate, pH, VOCs, total nitrogen, chloride, phosphate, total dissolved solids, and sulfate. These values were monitored and if detected, were compared against permit requirements. There were no permit violations of California RWQCB permit number R8-2002-0033-038; therefore, this objective was met.

## **6.7 REGULATORY ACCEPTANCE**

A letter of conditional acceptance for the MBfR for treatment of nitrate was received the CDPH on July 26, 2013 (Appendix B). APTwater has installed an MBfR system at the Cucamonga Valley Water District for full-scale treatment of nitrate. The system is called ARoNite™ (stands for Autotrophic Reduction of Nitrate). In December of 2011, the system became NSF 61-certified. The optimization data gathered from this study were used to help develop the design and operations of the Cucamonga Valley Water District facility. This system is in the process of being permitted by CDPH for full-scale operation.

## **7.0 COST ASSESSMENT**

The cost assessment was conducted for an MBfR treating nitrate and not perchlorate because the 6- $\mu\text{g/L}$  performance objective for perchlorate removal was not achieved. This section provides the cost assessment for a full-scale 1000-gallon per minute (gpm) MBfR system under six scenarios. Each scenario was assessed during a 30-year life cycle. Since the MBfR process did not meet treatment objectives for perchlorate, the assessment focused solely on nitrate removal. The assessment was performed to obtain a generic cost data considering engineering, equipment, construction, and operational costs. The test data from the Rialto Well 22 site were used as a basis for developing the estimate. Comparisons were made between the MBfR and conventional IX and a packed bed or fixed-bed bioreactor (FXB). Additional details are provided in the Final Report (Evans et al., 2013).

### **7.1 COST MODEL**

The purpose of the capital cost estimate is to assess the generic project cost for system installation and construction. The capital cost includes equipment, installation, and construction, as well as standard line items to account for indirect costs. Equipment costs were obtained from system suppliers. Site installation and construction costs were estimated from the project team's experience on similar construction projects. A 30-year amortized cost was calculated from the total installed cost, assuming a 2.0% real discount rate obtained from the Office of Management and Budget. Annualized operational costs are estimated for a 30-year plant life cycle with 2.0% real discount rate from Office of Management and Budget. Operations labor, water pumping, disinfection chemical, minor equipment, and lighting power were not included to be consistent with previous cost analyses (Brown et al., 2008).

#### **7.1.1 MBfR System Design Basis**

The MBfR system consists of multiple vessel skids containing membrane modules and auxiliary equipment for aeration, filtration, and disinfection. Figure 14 shows a three-dimensional rendering of an example MBfR system with one vessel skid and one auxiliary skid. Three nitrate treatment goals were selected for a 1000-gpm full-scale MBfR system: 1) 28 mg-N/L of influent and 4.0 mg-N/L effluent, 2) 10 mg-N/L of influent and 6.8 mg-N/L effluent, and 3) 18 mg-N/L of influent and 6.8 mg-N/L of effluent (Table 4). In all of these scenarios, a portion of the 1000-gpm stream would be treated by the MBfR to 0.5 mg-N/L and the remaining untreated water would be blended with the treated water to meet the above-stated effluent nitrate goal. Scenario 1 has a nitrate concentration similar to the previously published work on biological treatment technologies (Brown et al., 2008; Webster and Togna, 2009) and is included in this study for comparison. Scenarios 2 and 3 were included to demonstrate mid-range and high-range nitrate loading, respectively. Scenario 2 has a nitrate concentration equal to that observed during the WVWD demonstration. Scenario 3 has a nitrate concentration in excess of the MCL of 10 mg-N/L to simulate treatment of a water source that would actually require treatment. The three treatment goals were applied to two MBfR system designs: a design using the same process used in the demonstration (Scenarios 1, 2 and 3) and a design based on results from the demonstration and APTwater's continued process development and optimization (Scenario 4, 5 and 6). The modified design was incorporated in the construction of the Cucamonga Valley Water District

MBfR for nitrate treatment. It includes several enhancements to increase system efficiency and decrease wastewater generation.

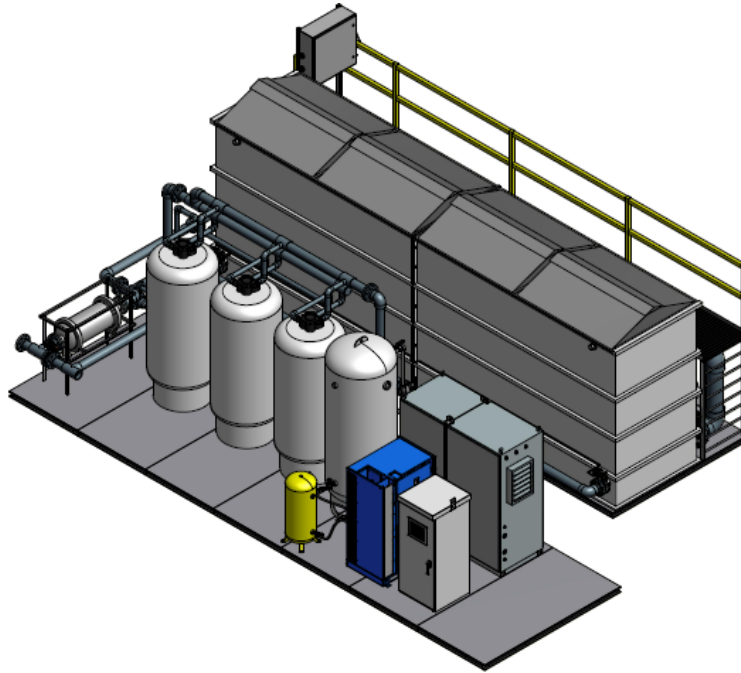


Figure 14. 3-D rendering of an example MBfR system.

Table 4. MBfR system design parameters.

Component	Units	Scenario					
		Based on Demonstration Results			Based on Optimized System Data from APTwater		
		1	2	3	4	5	6
Influent Water Quality							
Flow rate	gpm	1000	1000	1000	1000	1000	1000
Temperature	Deg C	20	20	20	20	20	20
pH	SU	7.5	7.5	7.5	7.5	7.5	7.5
Total dissolved solids	mg/L	260	260	260	260	260	260
Oxygen	mg/L	6	6	6	6	6	6
Sulfate	mg-SO <sub>4</sub> /L	20	20	20	20	20	20
Nitrate	mg-N/L	6.3	10.2	18.1	6.3	10.2	18.1
	mg-NO <sub>3</sub> /L	28	45	80	28	45	80
MBfR System Flow Distribution							
Total flow rate	gpm	1000	1000	1000	1000	1000	1000
Bypass flow rate	gpm	601	649	357	601	649	357
MBfR system flow rate	gpm	399	351	643	399	351	643
Operating Conditions							
Hydrogen excess	%	100	100	100	30	30	30
Sparge interval	hours	12	12	12	24	24	24
Nitrate, MBfR effluent	mg-N/L	0.5	0.5	0.5	0.5	0.5	0.5
Nitrate, after blending with bypass stream	mg-N/L	4.0	6.8	6.8	4.0	6.8	6.8

### 7.1.2 Ion Exchange System Design Basis

IX is a common water treatment process used to remove various ionic species from water and wastewater. In this study, the cost of nitrate removal by the IX system was estimated and compared to the MBfR system. Table 5. summarizes design parameters of a regenerable IX system. The IX system was designed to treat 1000 gpm with the same treatment goals established for Scenarios 1 to 3 (Table 5). The IX system consists of three IX vessels along with pre-filter skids, a brine regeneration system, and a regeneration waste storage system.

**Table 5. IX system design parameters.**

Component	Units	Scenario		
		1	2	3
Influent Water Quality				
Flow rate	gpm	1000	1000	1000
Temperature	Deg C	20	20	20
pH	SU	7.5	7.5	7.5
Total dissolved solids	mg/L	260	260	260
Oxygen	mg/L	6	6	6
Sulfate	mg-SO <sub>4</sub> /L	20	20	20
Nitrate	mg-N/L	6.3	10.2	18.1
IX Flow Distribution				
Total flow rate	gpm	1000	1000	1000
Bypass flow rate	gpm	280	280	280
IX flow rate	gpm	720	720	720
Effluent Treatment Goals (post-blending)				
Nitrate	mg-N/L	4.0	6.8	6.8

## 7.2 COST DRIVERS

The main drivers for the capital cost are the nitrate concentration in influent water and the target nitrate concentration in effluent water. Because the MBfR system can achieve an effluent nitrate concentration down to 0.5 mg-N/L or less, it is not necessary to treat the entire influent stream with MBfR to meet target effluent concentrations. Hence, part of influent water can bypass the MBfR system and be blended with the MBfR effluent to meet the target nitrate concentration. A higher bypass ratio requires a smaller equipment size, which will reduce the capital cost. One of the main drivers for the operational cost of the MBfR system is electricity for recirculation pumps, which can account for up to 60% of the cost.

## 7.3 COST ANALYSIS

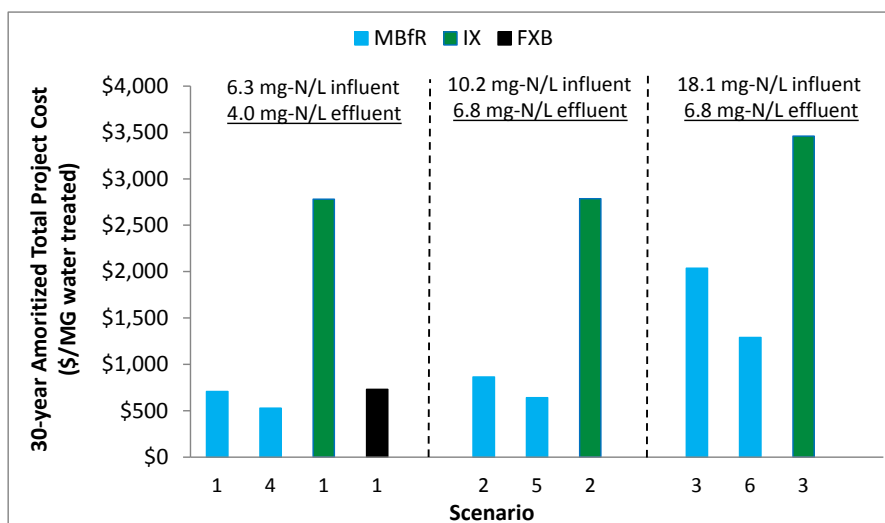
Table 6 shows the capital, operating, and total costs for MBfR and IX systems under different operating scenarios. Assumptions including unit costs are presented in Appendix C. The operational cost of the IX is much higher than that of the MBfR. While wastewater from the MBfR system, which is mostly from media backwash waste and MBfR sparging water, can be discharged through the municipal sanitary sewer, wastewater generated during IX regeneration cannot be directly discharged to the municipal sewer mainly due to the high salt concentration. Because of this, the IX operational cost is largely affected by the wastewater discharge, and costs can vary widely by site. The MBfR was also compared with a previous study, ESTCP project

200544, “Direct Fixed-Bed Biological Perchlorate Destruction Demonstration” (Brown et al., 2008). Figure 15 shows a cost comparison between the MBfR, IX, and FXB systems for a 1000-gpm system and water quality outlined under Scenario 1. The MBfR cost can be lower or equivalent to competing biological reduction technologies.

**Table 6. Comparison of capital, operating, and lifecycle costs for nitrate removal to 0.5 mg-N/L.**

	Scenario					
	Based on Demonstration Results			Based on Optimized System Data from APTwater		
	1	2	3	4	5	6
Flow rate <sup>1</sup> (gpm)	1000	1000	1000	1000	1000	1000
Oxygen (mg/L)	6	6	6	6	6	6
Sulfate (mg/L)	20	20	20	20	20	20
Nitrate (mg-N/L)	6.3	10.2	18.1	6.3	10.2	18.1
<b>Total Installed Cost</b>						
MBfR	\$4,986,700	\$6,007,700	\$13,635,500	\$3,757,100	\$4,639,500	\$8,636,300
IX	\$4,510,800	\$4,510,800	\$4,510,800	NA	NA	NA
<b>Annual Operating Cost, 30 Year Amortized</b>						
MBfR	\$149,000	\$185,800	\$463,100	\$110,100	\$129,600	\$293,200
IX	\$1,261,800	\$1,265,100	\$1,620,000	NA	NA	NA
Life						
<b>Annual Total Project Cost, 30 Year Amortized (\$)</b>						
MBfR	\$371,700	\$454,100	\$1,072,000	\$277,900	\$336,800	\$678,900
IX	\$1,463,300	\$1,466,600	\$1,821,500	NA	NA	NA
<b>Annual Total Project Cost, 30 Year Amortized (\$/MG)</b>						
MBfR	\$706	\$863	\$2037	\$528	\$640	\$1290
IX	\$2781	\$2787	\$3462	NA	NA	NA

<sup>1</sup> Listed flow rate is total flow rate. Only a portion of the total flow rate is treated by MBfR or IX. The remainder bypasses the treatment system and is blended to achieve regulatory limits. The amount of bypass varies per scenario and treatment technology as described in the ESTCP Final Report (Evans et al., 2013).



**Figure 15. Comparison of MBfR 30-year amortized capital and operating costs with IX and FXB operating at 1000 gpm.**



## 8.0 IMPLEMENTATION ISSUES

The MBfR system for treatment of nitrate and production of potable water was shown to be effective. The MBfR system is ready for applications involving treatment of drinking water sources contaminated with nitrate. Implementation for treatment of nitrate requires meeting necessary permitting regulations and that the key findings from this demonstration are integrated into a full-scale process. The MBfR can be designed to treat source waters with different nitrate concentrations. Sulfate will not affect treatment of nitrate because the MBfR is not operated under sufficiently reducing conditions when treating nitrate. Treatment of perchlorate to less than 6 µg/L was not possible and requires further development. The parallel research conducted by ASU provides possible ways to address this current limitation (Rittmann et al., 2013).

All applicable Federal and state regulations and requirements must be met for a full-scale MBfR system for potable water treatment including, but not limited to, the following:

- Compliance with primary drinking water standards for nitrite,
- Filtration to remove suspended solids and bacteria, and
- Disinfection to ensure that the potable water supply does not contain pathogenic bacteria (e.g., *E. coli*, fecal coliforms, and total coliforms) or elevated levels of heterotrophic bacteria.

While there are currently no Federal regulations for perchlorate in place, the USEPA has established an Interim Drinking Water Health Advisory of 15 µg/L. In February 2011, USEPA released the determination that perchlorate met the SDWA criteria for regulation and USEPA is currently in the process of establishing an MCL (Lehman and Subramani, 2011). The CDPH has developed rules that are more stringent and established a state MCL of 6 µg/L as of October 2007.

APTwater provides a commercially available MBfR skid system, called ARoNite™. The system includes MBfR vessels and auxiliary equipment, which may include downstream processing (aeration, media filtration, disinfection), based on customer requirements. Procurement of compressed or liquefied gases can be accomplished through a variety of national vendors. Gas generators are specialized pieces of equipment but are available from several manufacturers. Gas manifolds and distribution systems are not off-the-shelf and will require engineering design and custom fabrication.

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## APPENDIX A

### POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role In Project
Andrea Leeson	ESTCP 4800 Mark Center Drive Suite 17D08 Alexandria, VA 22350	Phone: 571-372-6398 Email: <a href="mailto:Andrea.Leeson.civ@mail.mil">Andrea.Leeson.civ@mail.mil</a>	ESTCP Environmental Restoration Program Manager
Patrick Evans	CDM Smith 14432 S.E. Eastgate Way, Suite 100 Bellevue, WA 98007	Phone: 425-519-8300 Cell: 206-351-0228 Email: <a href="mailto:evanspj@cdmsmith.com">evanspj@cdmsmith.com</a>	Principal Investigator
Bruce Rittmann	Arizona State University Biodesign Institute 1001 South McAllister Ave. P. O. Box 875801 Tempe, AZ 85287-5801	Phone: 480-727-0434 Cell: 847-804-2598 Email: <a href="mailto:rittmann@asu.edu">rittmann@asu.edu</a>	Co-Principal Investigator
Tom Crowley	West Valley Water District 855 West Base Line Road Rialto, CA 92376	Phone: 909-875-1804 x702 Cell: 909-213-7055 Email: <a href="mailto:tcrowley@wvwd.org">tcrowley@wvwd.org</a>	WVWD Site Owner
David Friese	APTwater 2495 Eastland Way Pleasant Hill, CA 94523	Phone: 925-977-1811 x308 Cell: 925-708-0480 Email: <a href="mailto:dfriese@aptwater.com">dfriese@aptwater.com</a>	Project Manager
Ryan Overstreet	APTwater 2495 Eastland Way Pleasant Hill, CA 94523	Phone: 925-977-1815 x305 Cell: 925-360-7206 Email: <a href="mailto:roverstreet@aptwater.com">roverstreet@aptwater.com</a>	Process Engineer
Eva Opitz	CDM Federal Programs 1050 North Reed Station Road, Suite D Carbondale, IL 62902	Phone: 618-351-4530 Email: <a href="mailto:opitzem@cdmsmith.com">opitzem@cdmsmith.com</a>	Program Manager
Jennifer Smith	CDM Smith 14432 S.E. Eastgate Way, Suite 100 Bellevue, WA 98007	Phone: 425-519-8300 Email: <a href="mailto:smithjl@cdmsmith.com">smithjl@cdmsmith.com</a>	Project Engineer
Eugene Leung	California Department of Public Health 850 Marina Bay Parkway Building P, 1st Floor Richmond, CA 94804	Phone: 510-620-3460 Email: <a href="mailto:Eugene.Leung@cdph.ca.gov">Eugene.Leung@cdph.ca.gov</a>	Regulatory Oversight
Sean McCarthy	California Department of Public Health 464 W. 4th Street, Room 437 San Bernardino, CA 92401	Phone: 909-383-4328 Email: <a href="mailto:Sean.McCarthy@cdph.ca.gov">Sean.McCarthy@cdph.ca.gov</a>	Regulatory Oversight

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## **APPENDIX B**

### **CDPH LETTER OF CONDITIONAL ACCEPTANCE**

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State of California—Health and Human Services Agency  
California Department of Public Health



EDMUND G. BROWN JR.  
Governor

July 26, 2013

Mr. John Bosler  
Chief Operations Officer  
Cucamonga Valley Water District  
P.O. Box 638  
Rancho Cucamonga, CA 91730

Mr. David Frieze  
ARoNite Technology Director  
APTwater, Inc.  
2516 Verne Roberts Circle, Suite H-102  
Antioch, CA 94509

**CONDITIONAL ACCEPTANCE OF ARONITE BIOLOGICAL TREATMENT FOR THE  
PRODUCTION OF DRINKING WATER FROM NITRATE CONTAMINATED WATER**

Dear Mr. Bosler and Mr. Frieze:

The Water Treatment Committee (WTC) of the Drinking Water Program in the California Department of Public Health (Department) has reviewed the following documents submitted with your request to gain acceptance of ARoNite (Autotrophic Reduction of Nitrate) biological treatment as a means of removing nitrate from source waters prior to distribution as part of the public water supply.

"Well 23 ARoNite 30 Day Demonstration Report, April 12, 2012" prepared by APTwater for Cucamonga Valley Water District

"Well 23 ARoNite Extended Demonstration Report, January 21, 2013" prepared by APTwater for Cucamonga Valley Water District

Based on the review of the above pilot study reports, the WTC hereby confirms that the ARoNite biological treatment process has been demonstrated to remove nitrate from some sources of water. The ARoNite process is a hydrogen based membrane biofilm biological treatment system for the removal of nitrate. The ARoNite system uses native microorganisms present in the groundwater and hydrogen gas as the electron donor for microbial respiration. The biological treatment process occurs in a proprietary sealed treatment vessel where membranes are used to deliver hydrogen gas to the biofilm.

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Division of Drinking Water and Environmental Management, Drinking Water Technical Operations Section  
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Telephone: (510) 620-3474 Fax: (510) 620-3455  
Internet Address: <http://www.cdph.ca.gov/programs/Pages/DWP.aspx>

Mr. John Bosler and Mr. David Frieese  
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The pilot study result indicates that a properly designed and operated ARoNite biological treatment system can be used as one of the unit processes for the removal of nitrate from some water sources. Thus it can be incorporated into an overall drinking water treatment plant. Nevertheless, we consider the ARoNite biological treatment system to be capable of nitrate removal with several important caveats that have been incorporated into the conditions presented below.

The WTC accepts the ARoNite biological treatment system to remove or reduce nitrate from some source water(s) that might be used for potable supply subject to the following conditions:

1. The system is operated in a manner that maximizes steady state conditions and minimizes intermittent production flow rates (e.g., a plant operated 24 hours a day, 7 days a week).
2. Continuous on-line monitoring systems for water flow, nitrate, turbidity, chlorine residual and dissolved oxygen shall be incorporated into the process design with adequate alarm strategies detailed in the water system's operation plan.
3. Site-specific tests are required to determine the impact of seasonal and temporal variations in water quality (nitrate concentration, temperature, available micro and macro nutrients, and/or hydraulic loading rates, etc.) on process performance. For example, it is anticipated that the hydrogen feed requirement will vary as a function of source water quality, so the impact(s) of variable nitrate concentrations (in time and magnitude) on finished water quality needs to be evaluated. The site-specific verification testing should represent worst-case conditions and the testing periods must cover the time during the seasonal and temporal variations in water quality.
4. Nitrate reduction process control shall be based on the constant influent flow with variable hydrogen pressure scheme that was demonstrated during the extended demonstration period.
5. Filtration treatment process control shall be based on the use of an optimum dose of coagulant that includes adequate flash mixing and an acceptable filter design.
6. Source of the microbiological seed must be identified and characterized as not containing human pathogens, except when indigenous biota are selected to inoculate the bed. The use of indigenous microorganisms to "seed" the reactor renders this condition moot.

7. All chemicals used in the system must be NSF/ANSI standard 60 certified by an ANSI accredited testing organization.
8. All materials that come into direct contact with the source water must be NSF/ANSI standard 61 certified by an ANSI accredited testing organization.
9. A pressure sensor with alarm should be installed on the hydrogen feed system.
10. Following biological treatment, the filtration, disinfection and other treatment processes will be required to meet the following performance standards:
  - a. 4-log virus inactivation must be achieved by the end of the disinfection treatment process.
  - b. Treated water must be coliform free. Weekly or monthly samples collected at the end of the disinfection treatment process will be required.
  - c. Treated water must contain HPC of less than 500 cfu/mL. Weekly or monthly samples collected at the end of the disinfection treatment process will be required.
  - d. Individual filtered water effluent turbidity shall be 0.3 NTU or less, 95% of the time. Continuous monitoring of filter effluent will be required.
  - e. Corrosivity of the effluent water must be monitored and controlled prior to distribution, if necessary. Daily treated water pH reading of the plant effluent will be required.
  - f. Distribution system disinfectant by-products samples must be collected based on the Stage 2 Disinfectant / Disinfection By-Products Rule and must comply with the Locational Running Annual Average (LRAA) for TTHM and HAA5 MCLs.
  - g. Treated water must meet all secondary standards.
  - h. Treated water needs to have sufficient dissolved oxygen to stabilize the water prior to distribution to consumers.
11. Proper operator certification of the facility will be required based on the complexity of the full scale treatment system.
12. An operator training program for the biological treatment system shall be provided as part of the start-up process for the full scale treatment system.

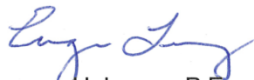
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We note that membrane biofilm reactor biological treatment has not been proven to work on all water sources. Therefore, additional testing will be required to confirm the treatment system's performance prior to full scale installations at other use sites. To ensure the acceptability of the study approach, prior to starting, the local CDPH Drinking Water Program District Engineer should be consulted to ensure that the study is conducted in sufficient detail so that adequate information is gathered to identify the critical design and operating factors of the full scale treatment plant.

Be advised that the approval for the design and use of this technology in any drinking water application will be handled on a case-by-case basis by the Drinking Water Program's district offices. The individual district offices based on specific site requirements may specify additional unit treatment processes as well as require additional pilot testing or full-scale demonstration of the treatment process. Approval is granted through the domestic water supply permitting process. Information such as the study results, technical drawings, plans and specifications will need to be submitted with the application and will be used for the development of the water supply permit.

We would like to thank you and your colleagues for working with us during the development and testing of this technology. Should you have any questions regarding the content of this letter, please free to contact me at (510) 620-3460.

Sincerely,



Eugene H. Leung, P.E.  
Senior Sanitary Engineer  
Technical Operations Section

cc: Water Treatment Committee

## **APPENDIX C**

### **COST ASSUMPTIONS**

#### **1.0 CAPITAL COSTS**

The purpose of the capital cost estimate is to assess the generic project cost for system installation and construction. The capital cost includes equipment, installation, and construction, as well as standard line items to account for indirect costs. Equipment costs were obtained from system suppliers. Site installation and construction costs were estimated from the project team's experience on similar construction projects. Total installed cost and line items included in the cost estimate were calculated from the cost model in Table C.1. A 30-year amortized cost was calculated from the total installed cost, assuming a 2.0% real discount rate obtained from the Office of Management and Budget.

It should be noted that for an objective comparison of capital costs, the following items on direct and indirect costs, which can vary greatly by site and/or project conditions, are not considered in this study:

- Land acquisition costs
- Major site improvement work, such as fill material or substantial clearing
- Raw water resource development and pumping/piping system
- Finished water storage
- Laboratory or staff office space
- Bringing utilities to/from the site (water, wastewater, power, communications)
- Environmental assessment of site
- Owner administration and legal fees

While effort was made to provide a realistic cost estimate, caveats must be placed that the installation costs are only applicable for systems operating at 1000 gpm. For larger systems, though scaling of the costs may be directly proportional in some cases (i.e., electrical design), it is not always directly scaled. For example, with larger installations, significantly more design, labor, and materials would be required for structural design. Although a cost reduction might be observed based on an economy of scale, this reduction may be offset by the need for larger delivery trucks, fuel fees, additional labor, etc.

**Table C.1. Cost estimate model.**

<b>Cost Element</b>	<b>Basis</b>
Equipment installed cost	From System Suppliers
Civil and construction cost	Based on system footprint, including excavation, grading, and 2-foot concrete foundation
Piping and mechanical installed cost	Assumed \$45/square foot
Electrical, Instrumentation, and controls installed cost	Assumed 10% of the total installed cost for electrical and 2% for instrumentation and controls
<b>Subtotal Direct Cost</b>	Sum of the Above
Permit fees and sales taxes	12% of Subtotal Direct Cost
Bond and insurance	3% of Subtotal Direct Cost
<b>Subtotal A</b>	Subtotal Direct Cost + Permit Fees and Sales Taxes + Bond and Insurance
General conditions	10% of Subtotal A
Contractor overhead and profit	15% of Subtotal A
<b>Subtotal B</b>	Subtotal A + General Conditions + Contractor Overhead and Profit
Contingency	25% of Subtotal B
<b>Subtotal C</b>	Subtotal B + Contingency
Engineering design services	10% of Subtotal C
<b>Total Installed Cost</b>	Subtotal C + Engineering Design Services

## 2.0 OPERATIONAL COSTS

Annualized operational costs are estimated for a 30-year plant life cycle with 2.0% real discount rate from Office of Management and Budget. Table C.2 shows the calculation basis. Unit costs were based on quotes from equipment vendors and APTwater.

**Table C.2. Operations cost calculation basis.**

<b>Component</b>	<b>Units</b>	<b>Value</b>
<b>MBfR Costs</b>		
Hydrogen, on-site generation	\$/lb	0.59
Carbon dioxide	\$/lb	0.24
Coagulant	\$/lb	1.1
75% phosphoric acid	\$/lb	0.85
Power	\$/kWh	0.12
Membrane replacement cycle	yr	10
Membrane module cost	Each	\$1700
Media filter replacement cycle	yr	10
Aeration	0.058	kWh/1000 gal
<b>Prefiltration/IX Resin Costs</b>		
Prefilter replacement cycle	yr	1
Prefilter replacement cost	Each	\$8000
IX resin replacement cycle	yr	10
IX resin replacement cost	Each	\$18,000
Salt for IX regeneration	\$/ton	130
IX regeneration waste discharge fee	\$/gal	0.1
IX regeneration wastewater generation	gal/gal treated	0.024 to 0.030

The following items are excluded from the operational cost estimate:

- Operation labor
- Raw and product water pumping
- Disinfection chemical
- Minor equipment and lighting power

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